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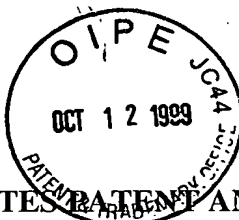
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03C0  
PATENT #5

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of )

Johan Olof Anders ROBERTSSON and )  
Andrew CURTIS )

Application N°: 09/396,052 )

Filing Date: September 15, 1999 )

Title: SEISMIC DETECTION APPARATUS )  
AND RELATED METHOD )

Group:

Examiner:

Docket N°: 57.0307

I hereby certify that this correspondence is being deposited with the United States Postal Service on the date shown below with sufficient postage as first class mail in an envelope addressed to: Assistant Commissioner for Patents, Washington, D.C. 20231 on  
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Washington, D.C. 20231

Sir:

Attached hereto are United Kingdom Patent Application Nos. 9820049.6, filed 16 September 1998; and 9906995.7, filed 29 March 1999, for the above-captioned application. Priority is claimed under 35 U.S.C. §119 and 37 CFR §1.55.

Respectfully submitted,

By: *William B. Batzer*

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Date: October 7, 1999

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INVESTOR IN PEOPLE

The Patent Office  
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## 1. Your reference

57.0307 GB NP1

## 2. Patent application number

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9906995.7

29 MAR 1999

## 3. Full name, address and postcode of the or of each applicant (underline all surnames)

Geco-Prakla (UK) Ltd / Schlumberger Holdings Ltd

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British Virgin Islands

Patents ADP number (if you know it)

If the applicant is a corporate body, give the country/state of its incorporation

6837810001  
United Kingdom

7284326001  
British Virgin Islands

## 4. Title of the invention

Seismic Detection Apparatus and Related Method

## 5. Name of your agent (if you have one)

MIRZA, Akram Karim

"Address for service" in the United Kingdom to which all correspondence should be sent (including the postcode)

c/o Schlumberger Cambridge Research Ltd  
High Cross, Madingley Road  
Cambridge  
CB3 0EL

Patents ADP number (if you know it)

6977299001

## 6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and (if you know it) the or each application number

Country

Priority application number  
(if you know it)

Date of filing

(day / month / year)

Great Britain

9820049.6

16 Sep 1998

## 7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application

Number of earlier application

Date of filing  
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## 8. Is a statement of inventorship and of right to grant of a patent required in support of this request? (Answer 'Yes' if:

YES

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Any other documents -  
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Signature

Date

26 March 1999

12. Name and daytime telephone number of person to contact in the United Kingdom MIRZA, Akram Karim 01223-325268

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29 MAR 1999

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**Statement of inventorship and of  
right to grant of a patent**

The Patent Office

Cardiff Road  
Newport  
Gwent NP9 1RH

1. Your reference **57.0307 GB NP1**

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2. Patent application number **9906995.7** **29 MAR 1999**  
(if you know it)

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3. Full name of the or of each applicant **Geco-Prakla (UK) Ltd / Schlumberger Holdings Ltd**

4. Title of the invention **Seismic Detection Apparatus and Related Method**

5. State how the applicant(s) derived the right from the inventor(s) to be granted a patent  
The Applicant(s) and the Employer(s) of the Inventor(s) are affiliated Schlumberger companies. The Applicant(s) derived the right to be granted a patent by virtue of agreement with the Employer(s) of the Inventor(s).

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7. I/We believe that the person(s) named over the page (and on any extra copies of this form) is/are the inventor(s) of the invention which the above patent application relates to.

Signature

Date



26 March 1999

8. Name and daytime telephone number of person to contact in the United Kingdom **MIRZA, Akram Karim** **01223-325268**

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Enter the full names, addresses and postcodes of the inventors in the boxes and underline the surnames

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Patents ADP number (if you know it): 7281447001

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Patents ADP number (if you know it): 7631187001

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### Seismic Detection Apparatus and Related Method

This invention relates to seismic detection apparatus and to a  
5 method of analysing data acquired by such apparatus.

#### BACKGROUND OF THE INVENTION

10 In seismic detection, a seismic source signal propagates through different rock substrates or strata within the earth, so producing compression waves (P-waves) and shear waves (S-waves) which can be analysed to determine the direction and extent of geological features in strata.

15 Generally a seismic source signal is produced, either on land, sea, or in a borehole, the source signal usually being produced as either acoustic or elastic energy. Some of the energy radiates downward through geological layers within the earth and is reflected in varying proportions at different layer boundaries and  
20 this reflected energy can be detected at the surface. Some of the energy within the seismic source signal propagates directly along the ground producing a wave noise signal known as ground-roll. To detect the acoustic reflections which are in the form of P-waves and S-waves, a linear or areal array of geophones is used to  
25 reinforce the reflected energy and to attenuate the energy associated with ground-roll so that a good signal to noise ratio can be achieved for the reflected wave components of interest.

30 It is desirable to be able to separate the P-wave and S-wave components of an elastic wave field as the separated components can be used more effectively to identify different characteristics than when combined. It is an aim of the present invention to provide improved separation of seismic signals into P-wave and S-waves.

## SUMMARY OF THE INVENTION

According to one aspect of the present invention, there is provided  
5 seismic detection apparatus comprising seismic detection means  
capable of detecting a plurality of seismic components over a  
selected volume.

Preferably the seismic detection means comprises a plurality of  
10 receivers spaced apart to enclose the selected volume. The  
receivers may include hydrophones, geophones, accelerometers or a  
combination of these, and preferably are adapted to detect seismic  
signals along three mutually orthogonal axes. Thus the receivers  
may be provided by three-component geophones.

15 Preferably the selected volume is formed by at least three  
receivers spaced within a plane and at least one receiver placed  
external to the plane, thereby to enclose the selected volume over  
which measurement of seismic signals occurs.

20 Preferably the receivers are spaced to form a tetrahedron with  
three receivers spaced to define a triangle within the plane and a  
fourth receiver placed external the plane but in line with the  
centroid of the triangle. Other configurations of spaced apart  
25 receivers may be used depending on the characteristics of the  
wavefield being measured, for example receivers may be spaced to  
form an octahedral volume, a cubic volume, or a spherical volume.  
Certain shaped volumes may be more appropriate for different uses,  
for example receivers spaced to form an octahedral volume may be  
30 more appropriate for use with permanent downhole sensors.

In a variant that is suitable for seismic acquisitions at a free  
surface boundary, i.e. particularly for land seismic acquisitions,  
the volume formed by the receivers can be reduced to a plane. Hence

with a minimum of three 3 component geophones the full wavefield can be determined using the free surface condition as constraints.

5 The seismic detection apparatus in accordance with the present invention is suitable for use on the surface, with the enclosed volume being achieved by placing one receiver further below the surface of the other receivers, for example by burying it beneath the surface. With marine and ocean bottom surveys, the volume may  
10 be defined by tethering the receivers at different water depths, for example by placing three receivers spaced apart at the same depth, and a fourth receiver at a different depth. The seismic detection apparatus according to the present invention is also of use in seismic detection is a transitions zone such as swamps and  
15 marshes, where again tethering of the receivers at different depths will define the enclosed volume.

The apparatus may also have all the receivers incorporated into one body for attaching to a wireline and using downhole, or for using  
20 permanently downhole. Such a permanent sensor is of particular advantage where monitoring of a reservoir or other geological feature over time is required. This may be appropriate when monitoring fluid flow occurring within a reservoir as permanent sensors can be used to detect natural seismicity resulting from  
25 fluid opening and closing micro-fissures within the substrates and producing micro-earthquakes. Whilst these micro-earthquakes produce very weak broadband signals, by use of permanent sensors, this activity can be detected and production adapted by remedial action such as acid to remove carbonate deposits, or fracturing  
30 rock with high pressure steam or water, so as to improve production efficiency.

Preferably the apparatus further comprises processing means which analyses detected seismic components from individual receivers to separate P-wave components from S-wave components. The processing means may be provided at substantially the same location as the receivers to allow for on-site processing, or remote from the receivers to allow off-site processing.

In surveys of the vertical component of seismic data, the receivers may be adapted to detect components along one axis and orientation of the receivers selected so as to permit processing of one-component data to identify P-wave components. Therefore the receivers may be provided by one-component geophones.

Preferably the spacing of the receivers is selected to be smaller than the wavelength of the detected seismic components. A preferred spacing is less than 1 m, more preferably between 0.05m and 0.50m, although larger spacings of up to a third of the shortest detected wavelength are possible, and thus the range may be between 1.5 and 15m.

In use, the apparatus may be operated to detect seismic signals over a time period of the order of five seconds where P-wave components are of principal interest, with any marginal S-wave component detected at that time being used to produce improvements in the signal to noise ratio.

Where a detection time of the order 10 to 15 seconds is used, both P-wave and S-wave components will be detected within the seismic signals and may be separated for multi-component inversion yielding images of reservoirs and other geological formations, and full reservoir characterisation.

In accordance with another aspect of the invention, there is provided a method of processing seismic data comprising acquiring seismic data relating to a wavefield over a selected volume of acquisition, and measuring the curl and divergence of the wavefield  
5 from the seismic data, to thereby identify seismic components within the seismic data.

As P-waves are curl free and S-waves divergence free, this allows the separate identification of P-wave and S-wave components. Up-  
10 going and down-going wavefield components in boreholes may also be identified from the seismic data. Attenuation of unwanted seismic components from data acquired downhole is also enabled, and noise sources such as ground roll, airwave and inter-sensor perturbations can be removed from the data by signal processing.

15 The method preferably further comprises averaging the curl and divergence over the selected volume of acquisition, and where appropriate acquiring seismic data over a selected period of time.

20 Additionally the method may further comprise defining the selected volume of acquisition to be small compared to the wavelength of seismic waves to be detected.

As described above, in a seismic acquisition at a free surface, the  
25 constraints imposed by the free surface enable the reduction of the acquisition volume to a acquisition surface where all receivers (minimum three) are located in a plane.

In another aspect of the invention, the representation theorem  
30 based filters used for removing multiples from Ocean Bottom Cable data as described in UK Patent Application No. 9900472.3 is modified to provide a method of separating the seismic data

acquired with the planar receiver configuration above into up- and downgoing wavefield.

These and other features of the invention, preferred embodiments  
5 and variants thereof, possible applications and advantages will become appreciated and understood by those skilled in the art from the detailed description and drawings following hereinafter.

#### BRIEF DESCRIPTION OF THE DRAWINGS

10 FIG. 1 shows an example of the distribution of seismic data over a specified period of time;

FIG. 2 shows one embodiment of seismic detection apparatus  
15 according to the present invention;

FIG. 3 shows a second embodiment of seismic detection apparatus according to the present invention;

20 FIG. 4 shows a tetrahedron used in explanation of a processing method according to the present invention;

FIG. 5 shows a planar configuration of receivers according to the present invention; and

25 FIG. 6 summarizes a processing method based on a planar receiver arrangement according to the present invention.

#### MODE(S) FOR CARRYING OUT THE INVENTION

30 In Figure 1, a typical hodogram of a three component marine shot gather survey is shown, where the x axis is the offset in metres and the y axis is time in seconds from the generation of a source



signal at  $t=0$ . A hodogram displays the different seismic components detected over a specified time-window. The first arrivals around  $t=1s$  predominantly comprise P-waves 10, 10'. Near-surface scattering and channelling in slower near-surface layers are revealed in the P-wave arrivals contained in the hodogram through some degree of elliptical motion. Following the P-wave arrivals is a relatively quiet section 12, 12' (where deeper reflections can be observed) until the S-wave arrivals 14, 14' are observed near  $t=3s$ . The S-waves also scatter and become channelled in the near-surface which causes ellipticity in the hodogram.

Following the S-wave arrivals are elliptically polarised Rayleigh waves 16, 16' (ground-roll). The innermost "cone" 20 of the section consists of strongly scattered energy that typically masks deeper reflections.

Noise in seismic data to a large degree comprises source-generated ground-roll and S-waves. Separating P-wave data from S-wave data is useful to reduce noise attenuation. Also P-wave data may be of primary interest with the complete removal of S-waves being preferred, for example in shallow seismic imaging for engineering or environmental purposes.

Measuring the P-wave and S-wave components of an elastic wavefield separately has several advantages. First, separation of P-waves and S-waves enables better and more accurate analysis of each separated component thus improving moveout analysis and Amplitude Versus Offset (AVO) analysis. Secondly heterogeneity in the near-surface (as well as deeper down in the crust) and rough surface topography, scatter S-waves to a greater extent than P-waves, with scattered S-waves significantly contributing to noise in seismic reflection data.

Figure 2 shows one embodiment of a seismic detection apparatus according to the present invention, with four three-component detectors, such as geophones or hydrophones, being placed to form an enclosed tetrahedral volume. Geophones are velocity motion  
5 sensors, with hydrophones being pressure sensors. Geophones 22, 24, 26 are arranged in a horizontal plane 30 with each geophone being spaced the same distance from the other two geophones, so as to form an equilateral triangle. The fourth geophone 32 is placed vertically below the centroid 34 of the equilateral triangle formed  
10 by geophones 22, 24, 26. Placing of geophone 32 external to the horizontal plane 30 is achieved by positioning the horizontal plane 30 on or close to the Earth's surface with the fourth geophone 32 dug to a position well below surface. Within a marine, ocean bottom or swamp environment, the arrangement of receivers is  
15 achieved by tethering three hydrophones and/or geophones at one depth and one hydrophone and/or geophone at a different depth.

An ideal tetrahedral volume is not essential, and thus for example two geophones placed external to horizontal plane 30 can be used.  
20

The geophones 22, 24, 26 are positioned one metre apart, although spacing will vary depending on the surrounding rock substrate and how fast waves travel within the substrate. The spacing of the geophones to form an enclosed volume 36 is chosen so that the  
25 wavefield is detected on a scale which is smaller than the wavelengths of interest. For wave frequencies of between 50 to 100 Hz with velocity ranging from 300-2000 m/s, the wavelength tends to be in the range 5 to 50 m. To record the wavefield over such a range, the spacing of the geophones is generally a third of the  
30 wavelength and generally in the range 1.0m to 15m, although may be as small as 0.05 m. The tetrahedron arrangement shown in Figure 2 uses the minimum number of geophones required to define an enclosed

volume, although other configurations with more geophones are possible, such as those forming an octahedron, cube or sphere.

The use of four three-component geophones distributed as shown in  
5 Figure 2 allows the separation of the wavefield into P-waves and S-waves. After the seismic data has been recorded either where acquisition of data is occurring or remote from the geophones, differences in geophone coupling can be removed by normalising separately the responses of each component at the corners of the  
10 tetrahedron. If required, more accurate compensation for coupling differences can be obtained by using information from adjacent tetrahedral arrays of geophones, while preserving the offset varying character of the seismic data. The geophone coupling may also be frequency dependent varying from geophone to geophone.

15  
The three-component geophones 22, 24, 26, 32 detect components of the seismic signal at three orthogonal axes. By measuring the curl of a displacement field  $\mathbf{u}(x, t)$  within the enclosed volume 36 and the divergence of the displacement field within the volume 36, it  
20 is possible to separate out the P-wave and S-wave components as P-waves have zero curl and S-waves have zero divergence.

With the array of geophones shown in Figure 3, the four geophones 40, 42, 44, 46 are one-component geophones. The array encloses a  
25 tetrahedral volume 50 once more, but the axis along which each one-component geophone measures is calculated and precisely implemented when positioning the apparatus to ensure that the divergence can be deduced from the single components measured. Measuring with single component geophones provides less information about the seismic  
30 signals. However at present 90% of seismic surveys only monitor the vertical component, and the apparatus of Figure 3 when used with a listening time of five seconds allows a substantial

improvement in the signal to noise ratio if looking principally for P-wave components.

Once data are acquired using the geophone array enclosing a volume,  
 5 separation of the wave-field into P-waves and S-waves or  
 improvement of the signal to noise ratio for P-wave components, can  
 be undertaken by use of the method described below.

The elastic wave equation for a displacement field  $\mathbf{u}(\mathbf{x}, t)$  in an  
 10 isotropic medium with Lamé parameters  $\lambda$  and  $\mu$  and density  $\rho$  can be  
 written as:

$$[1] \quad \rho \ddot{\mathbf{u}} = \mathbf{f} + (\lambda + 2\mu) \nabla(\nabla \cdot \mathbf{u}) + \mu \nabla \times (\nabla \times \mathbf{u})$$

15 Here  $\mathbf{f}$  denotes a distribution of body forces. Lamé's theorem (Aki  
 and Richards, 1980) states that there exist potentials  $\Phi$  and  $\Psi$  of  
 $\mathbf{u}$  with the following properties:

$$[2] \quad \mathbf{u} = \nabla \Phi + \nabla \times \Psi,$$

20

$$[3] \quad \nabla \cdot \Psi = 0,$$

$$[4] \quad \ddot{\Phi} = \frac{\Phi}{\rho} + \alpha^2 \nabla^2 \Phi,$$

25

$$[5] \quad \ddot{\Psi} = \frac{\Psi}{\rho} + \beta^2 \nabla^2 \Psi,$$

where  $\alpha$  and  $\beta$  are the P- and S- velocities. An elastic wavefield  $\mathbf{u}$   
 can thus be decomposed into its P- and S-wave components,  $\nabla \Phi$  and  $\nabla$   
 $\times \Psi$ , respectively. Equations [2] and [3] yield

$$[6] \quad \nabla \cdot \mathbf{u} = \nabla^2 \Phi ,$$

$$[7] \quad \nabla \times \mathbf{u} = \nabla \times \nabla \times \Psi$$

5

(Råde, L., and Westergren, N., 1988, BETA  $\beta$  Mathematics Handbook: Student litteratur, Lund.). By measuring the curl and the divergence of an elastic wavefield we can thus measure the P- and S-wave components separately.

10

The technique for P- and S-wave separation is based on recording the elastic wavefield around a small volume as compared to the wavelength. The volume may be of arbitrary shape, but the equations for wavefield separation are simplified if the volume has a known deterministic shape such as that of a tetrahedron, cube, octahedron or a sphere. A co-ordinate system that is appropriate for the geometry employed simplifies the equations further. The discussion of the method below uses a tetrahedron and the formulae are derived in Cartesian co-ordinates.

20

Figure 4 shows a tetrahedron with corner points  $\mathbf{P}_1$ ,  $\mathbf{P}_2$ ,  $\mathbf{P}_3$ , and  $\mathbf{P}_4$ . We denote the Cartesian co-ordinates of point  $\mathbf{P}_i$  by  $(x_i, y_i, z_i)$ .

Let  $\overline{\mathbf{P}_j \mathbf{P}_i}$  denote the vector that starts at  $\mathbf{P}_i$  and ends at  $\mathbf{P}_j$ . The volume of the tetrahedron in Figure 4,  $V_{\text{tetra}}$ , can be calculated from the absolute value of the determinant of the matrix  $M$  with the vectors  $\overline{\mathbf{P}_2 \mathbf{P}_1}$ ,  $\overline{\mathbf{P}_3 \mathbf{P}_1}$ , and  $\overline{\mathbf{P}_4 \mathbf{P}_1}$  as rows:

$$[8] \quad V_{\text{tetra}} = \frac{1}{6} |\det M|.$$

30 Gauss' theorem states

$$[9] \quad \iiint_V (\nabla \cdot \mathbf{u}) dV = \iint_S \mathbf{u} \cdot d\mathbf{S}$$

or alternatively,

$$[10] \quad \iiint_V (\nabla \times \mathbf{u}) dV = \iint_S \mathbf{u} \times d\mathbf{S} .$$

5 If the dimensions of the tetrahedron configuration in Figure 4 are small compared to the wavelength of  $\mathbf{u}$ , the mean values of the curl and divergence in equations [9] and [10] can be calculated from:

$$10 \quad [11] \quad \nabla \cdot \mathbf{u} \approx \frac{1}{V_{\text{tetra}}} \iiint_V (\nabla \cdot \mathbf{u}) dV$$

and

$$[12] \quad \nabla \times \mathbf{u} \approx \frac{1}{V_{\text{tetra}}} \iiint_V (\nabla \times \mathbf{u}) dV .$$

15 Moreover, the surface integrals on the right hand side of equations [9] and [10] reduce to four surface integrals respectively, over plane triangular surfaces.

20 Since the normal to the surface of the tetrahedron does not vary over each of the triangular sub-surfaces, equation [9] becomes

$$[13] \quad \iiint_V (\nabla \cdot \mathbf{u}) dV = \iint_{S_{123}} \mathbf{u} \cdot d\mathbf{S} \cdot \mathbf{n}_{123}$$

$$25 \quad + \iint_{S_{243}} \mathbf{u} \cdot d\mathbf{S} \cdot \mathbf{n}_{243}$$

$$+ \iint_{S_{142}} \mathbf{u} \cdot d\mathbf{S} \cdot \mathbf{n}_{142} \dots$$

$$+ \iint_{S_{134}} \mathbf{u} \, dS \cdot \mathbf{n}_{134},$$

where  $\mathbf{n}_{ijk}$  is the outward unit normal to the triangular subsurface  
 5  $S_{ijk}$  with corner points  $\mathbf{P}_i$ ,  $\mathbf{P}_j$  and  $\mathbf{P}_k$  (see Figure 4).

Where the side of the tetrahedron is small compared to the  
 wavelength of the elastic wavefield, the value of  $\mathbf{u}$  at any point on  
 one of the triangular surfaces of the tetrahedron can be calculated  
 10 by linear interpolation of the wavefield between the three corner  
 points of the triangle. The surface integral over  $S_{ijk}$  (using  
 linear interpolation between  $\mathbf{P}_i$ ,  $\mathbf{P}_j$  and  $\mathbf{P}_k$ ) then reduces to

$$[14] \quad \iint_{S_{ijk}} \mathbf{u} \, dS = \frac{A}{3} (x_i + x_j + x_k, y_i + y_j + y_k, z_i + z_j + z_k),$$

15 where  $A$  is the area of  $S_{ijk}$ . Since  $A\mathbf{n}_{ijk} = \overline{\mathbf{P}_j\mathbf{P}_i} \times \overline{\mathbf{P}_k\mathbf{P}_i} / 2$  we have

$$[15] \quad \iiint_V (\nabla \cdot \mathbf{u}) \, dV = \frac{1}{6} [$$

$$\begin{aligned} & (x_1 + x_2 + x_3, y_1 + y_2 + y_3, z_1 + z_2 + z_3) (\overline{\mathbf{P}_2\mathbf{P}_1} \times \overline{\mathbf{P}_3\mathbf{P}_1}) \\ & + (x_2 + x_4 + x_3, y_2 + y_4 + y_3, z_2 + z_4 + z_3) (\overline{\mathbf{P}_4\mathbf{P}_2} \times \overline{\mathbf{P}_3\mathbf{P}_2}) \\ & + (x_1 + x_4 + x_2, y_1 + y_4 + y_2, z_1 + z_4 + z_2) (\overline{\mathbf{P}_4\mathbf{P}_1} \times \overline{\mathbf{P}_2\mathbf{P}_1}) \\ & + (x_1 + x_3 + x_4, y_1 + y_3 + y_4, z_1 + z_3 + z_4) (\overline{\mathbf{P}_3\mathbf{P}_1} \times \overline{\mathbf{P}_4\mathbf{P}_1}) ] \end{aligned}$$

Equivalently, the curl of  $\mathbf{u}$  in  $V$  can be calculated as

$$\begin{aligned}
 [16] \quad \iiint_V (\nabla \times \mathbf{u}) dV = \frac{1}{6} [ & \\
 & (x_1 + x_2 + x_3, y_1 + y_2 + y_3, z_1 + z_2 + z_3) \times (\overline{P_2 P_1} \times \overline{P_3 P_1}) \\
 & + (x_2 + x_4 + x_3, y_2 + y_4 + y_3, z_2 + z_4 + z_3) \times (\overline{P_4 P_2} \times \overline{P_3 P_2}) \\
 & + (x_1 + x_4 + x_2, y_1 + y_4 + y_2, z_1 + z_4 + z_2) \times (\overline{P_4 P_1} \times \overline{P_2 P_1}) \\
 & + (x_1 + x_3 + x_4, y_1 + y_3 + y_4, z_1 + z_3 + z_4) \times (\overline{P_3 P_1} \times \overline{P_4 P_1}) ]
 \end{aligned}$$

Finally, the average values of the divergence and curl of  $\mathbf{u}$  within  $V$  are obtained from equations [11] and [12].

In this way, the divergence and curl of a wavefield can be calculated from a set of closely spaced measurements distributed in all spatial directions. A minimum of four measurement points is needed. The volume that is bounded by planes connecting these points is generally a tetrahedron and where the dimensions of the tetrahedron are small with respect to the wavelength of the wavefield, an assumption that the wavefield varies linearly along each side of the enclosed volume is possible. The average divergence and average curl can then be efficiently calculated using Gauss' theorem.

For instance the average divergence inside the tetrahedron is calculated from the volume integral of the divergence of the wavefield over the tetrahedron, divided by its volume. The volume integral can in turn be converted to four surface integrals over each side of the tetrahedron by using Gauss' theorem. If the



wavefield varies linearly over each side, these surface integrals are simply the volume of a prism where the base of the prism is the surface area and the heights of the three corners are the magnitude of the wavefield in the respective corners projected onto the normal of the surface.

The average curl of the wavefield is evaluated similarly. The same procedure can be used to calculate average curl and divergence over more general volumes.

10

Uncertainties in the actual geometry can be eliminated by allowing the exact locations of  $P_1$ ,  $P_2$ ,  $P_3$ , and  $P_4$  to vary subject to either minimising equation [16] over a window(s) with an identified P-event and/or minimising equation [15] over S-events. This technique may also serve as an alternative means for adjusting for the differences in geophone coupling over the tetrahedron.

For anisotropic media the decomposition of  $u$  into P- and S-wave components as described by equations [2], [3], [4] and [5] is strictly not valid since the (quasi) P- and S-waves in anisotropic media both have compressional and shear components. However, this is of secondary importance and the theory above will be approximately valid for most practical cases.

In heterogeneous media, the heterogeneities act as secondary sources and scatter the wavefield. The separation of a wavefield into P-waves and S-waves is not strictly valid in the vicinity of a source. However the P/S separation technique described herein is generally applicable for common heterogeneous and anisotropic Earth materials, as well as for isotropic materials as discussed above.

With the apparatus and associated method, P-wave and S-wave components in seismic data can be separated.

In addition attenuation of near-surface scattering is possible as much noise is of S-wave character and where the primary interest is to record P-wave data, S-waves can be removed by employing the configuration of four one-component geophones as shown in Figure 3.

Applications of seismic techniques do not only include hydrocarbon exploration but also environmental, engineering and groundwater exploration and imaging. For such applications, it is typically of interest to image or detect very shallow structures, as shallow as 1-100m. Near-surface generated noise is particularly severe in these applications and a configuration of receivers such as in Figure 3 is particularly advantageous for shallow seismics.

The invention also allows for the attenuation of ground-roll. Since ground-roll can be elliptically polarised, it will appear both in the separated P- and S-wave sections, but with lower amplitude in the separated P-wave sections.

P- and S-wave separation is of particular use for marine seismic data recorded at the seafloor, since the near-surface at the seafloor is generally is of a more homogeneous character than at land. The technique is of use in removing Scholte waves that typically contaminate ocean data. Moreover, measurements of the wavefield over a volume also allows for the separation of the wavefield into up- and down-going waves.

Figure 5 shows a receiver arrangement particular useful for land acquisition. It comprises three 3C (component) geophones 52, 54, 56 arranged in a plane on the surface of the survey terrain. Each component of each geophone is measured independently. Thus, the three geophones are connected to the recording or processing unit

58 via a total of nine channels 60. Cable 62 provides a signal transmission between the groups of geophones.

In this example, the calculations according to the above equations are modified by introducing the free surface boundary condition. This condition constraints the possible solutions for the wavefield such that it is no longer necessary to employ a (fourth) out-of-plane receiver to sample additional components of the wavefield.

Furthermore the free surface condition is introduced into a formalism known as the elastodynamic representation theorem. This theorem is used for example in the UK Patent Application No. 9900472.3 to derive filters for separating up- and downgoing wavefield in the case of ocean bottom acquisition.

Using the representation the representation theorem and the boundary conditions of a solid-air interface, the following equations for up/down going separation of particle velocities  $v$  recorded by the planar receiver arrangement can be obtained:

$$[17] \quad v_v^U(x) = \frac{1}{2} ( v_v(x) - F_{v_3}^{v_v}(x) * v_3(x) ),$$

$$[18] \quad v_3^U(x) = \frac{1}{2} ( v_3(x) - F_{v_v}^{v_3}(x) * v_v(x) ).$$

The subscripts  $n$  and  $m$  denote indices for the horizontal coordinate axes  $x$  and  $y$  (for the 2-D case they reduce to  $x$ ). The filters in equations [17] and [18] are

$$[19] \quad F_{v_3}^{v_v} = -2\partial_v(1 + 2k_\beta^{-2}\partial_\mu^2) g(k_\alpha) + 2k_\beta^{-2}\partial_3^2 g(k_\beta) \text{ and}$$

$$[20] \quad F_{v_v}^{v_3} = 2k_\beta^{-2}\partial_v(-2\partial_3^2 g(k_\alpha) + (k_\beta^2 + 2\partial_3^2)g(k_\beta)).$$

In particular for the two dimensional (2D) case ( in the frequency-wavenumber domain), using expressions for Green's functions in a homogeneous medium , equations [19] and [20] become:

5

$$[21] \quad F_{v_z}^{v_x} = \frac{k_x}{2} \left( \left( 1 - 2 \frac{k_x^2}{k_\beta^2} \right) \frac{1}{k_z^{(\alpha)}} - \frac{2}{k_\beta^2} k_z^{(\alpha)} \right) \text{ and}$$

$$[22] \quad F_{v_x}^{v_z} = - \frac{k_x}{2k_\beta^2} \left( 2k_z^{(\alpha)} - 2k_z^{(\beta)} + \frac{k_\beta^2}{k_z^{(\beta)}} \right),$$

where  $k_z^{(\alpha)} = \sqrt{k_\alpha^2 - k_x^2}$  is the vertical wavenumber for P-waves and

10 and  $k_z^{(\beta)} = \sqrt{k_\beta^2 - k_x^2}$  is the vertical wavenumber for S-waves.

Filters for partial derivatives of velocities (e.g. divergence and curl) can be obtained following the approach used in the UK Patent Application No. 9900472.3.

15

## CLAIMS

- 5 1. Seismic detection apparatus comprising seismic detection means  
capable of detecting a plurality of seismic components over a  
selected volume.
- 10 2. Seismic detection apparatus according to claim 1, wherein the  
seismic detection means comprises a plurality of receivers  
spaced apart to enclose the selected volume.
- 15 3. Seismic detection apparatus according to claim 2, wherein the  
receivers include geophones.
4. Seismic detection apparatus according to claim 2 or claim 3,  
wherein the receivers include hydrophones.
- 20 5. Seismic detection apparatus according to any of claims 2 to 4,  
wherein the receivers include accelerometers.
- 25 6. Seismic detection apparatus according to any of the preceding  
claims, wherein the seismic detection means is adapted to  
detect seismic signals along three mutually orthogonal axes.
- 30 7. Seismic detection apparatus according to any of claims 2 to 6,  
wherein the selected volume is formed by at least three  
receivers spaced within a plane and at least one receiver  
placed external to the plane, thereby to enclose the selected  
volume over which measurement of seismic signals occurs.
8. Seismic detection apparatus according to claim 7, wherein the  
receivers are spaced to form a tetrahedron, with three

receivers spaced to define a triangle within the plane and a fourth receiver placed external the plane but in line with the centroid of the triangle.

- 5 9. Seismic detection apparatus according to any of claims 2 to 8, further comprising processing means which analyses detected seismic components from individual receivers to separate P-wave components from S-wave components.
- 10 10. Seismic detection apparatus according to claim 9, wherein the processing means is provided at substantially the same location as the receivers to allow for on-site processing.
11. Seismic detection apparatus according to claim 9, wherein the  
15 processing means is provided remote from the receiver to allow off-site processing of detected seismic components.
12. Seismic detection apparatus according to any of claims 2 to 5 and 7 to 11, wherein the receivers are adapted to detect  
20 components along one axis and orientation of the receivers is selected so as to permit processing of one-component data to identify P-wave components within the plurality of seismic components.
- 25 13. Seismic detection apparatus according to any of claims 3 to 12, wherein the spacing of the receivers is selected to be smaller than the wavelength of the detected seismic components.
- 30 14. Seismic detection apparatus according to any of the preceding claims, when attached to a wireline for placing temporarily downhole.

15. Seismic detection apparatus comprising at least three 3C  
(component) geophones located in a plane at the surface  
wherein said at least three geophones are spaced less than 1m  
of each other to form a receiver cluster and each of the three  
5 components of each of said geophones is recorded individually.
16. Seismic detection apparatus in accordance with claim 15,  
comprising a plurality of the receiver clusters distributed  
over a land survey area.
- 10 17. Seismic detection apparatus in accordance with claim 15,  
wherein the three components of each of the geophones are  
transmitted to a processing unit to calculate an approximation  
of the full wavefield at the position of the cluster.
- 15 18. Seismic detection apparatus in accordance with claim 15,  
wherein the three components of each of the geophones are  
transmitted to a processing unit to calculate an approximation  
of the full wavefield at the position of the cluster making  
20 use of a free surface boundary condition
19. Use of seismic detection apparatus according to any of the  
preceding claims on surface.
- 25 20. Use of seismic detection apparatus according to any of claims  
1 to 13 in a marine environment or transition zone.
- 30 21. A method of processing seismic data comprising acquiring  
seismic data relating to a wavefield over a selected volume of  
acquisition, and measuring the curl and divergence of the  
wavefield from the seismic data, to thereby identify seismic  
components within the seismic data.

22. A method of processing seismic data comprising acquiring seismic data relating to a wavefield over a selected plane of acquisition defined by at least three 3C (component) geophones said at least three geophones being spaced less than 1m of each other to form a receiver cluster and each of the three components of each of said geophones being recorded individually, and measuring the curl and divergence of the wavefield from the seismic data, to thereby identify seismic components within the seismic data.

23. A method of processing seismic data according to claim 21 or 22, wherein P-wave and S-wave components are separately identified.

24. A method of processing seismic data according to, wherein up-going and down-going wavefield components are identified from the seismic data.

25. A method of processing seismic data according to any of claims 21 to 24, enabling attenuation of unwanted seismic components from seismic data.

26. A method of processing seismic data according to any of claims 21 to 25, further comprising averaging the curl and divergence over the selected plane or volume of acquisition.

27. A method of processing seismic data according to any of claims 21 to 25, further comprising acquiring seismic data over a selected period of time.

28. A method of processing seismic data according to any of claims 21 to 26, further comprising defining the selected plane or



volume of acquisition to be small compared to the wavelength of seismic waves to be detected.

- 5      29. Apparatus and method substantially as herein described and particularly with reference to and as illustrated in the accompanying drawings.

## ABSTRACT

Seismic detection apparatus comprising seismic detection means  
5 capable of detecting a plurality of seismic components over a  
defined tetrahedral volume (36) is provided. The seismic detection  
means comprises four three-component geophones (22, 24, 26, 32).  
Seismic data acquired by the geophones is processed to separate P-  
wave components from S-wave components. The geophones are spaced  
10 apart by distances smaller than the wavelength of the detected  
seismic components. The apparatus may be used on surface or in a  
marine environment or transition zone. A method of processing  
seismic data is also provided comprising acquiring seismic data  
relating to a wavefield over a selected volume of acquisition, and  
15 measuring the curl and divergence of the wavefield from the seismic  
data, to thereby identify seismic components within the seismic  
data.

[ Figure 2]

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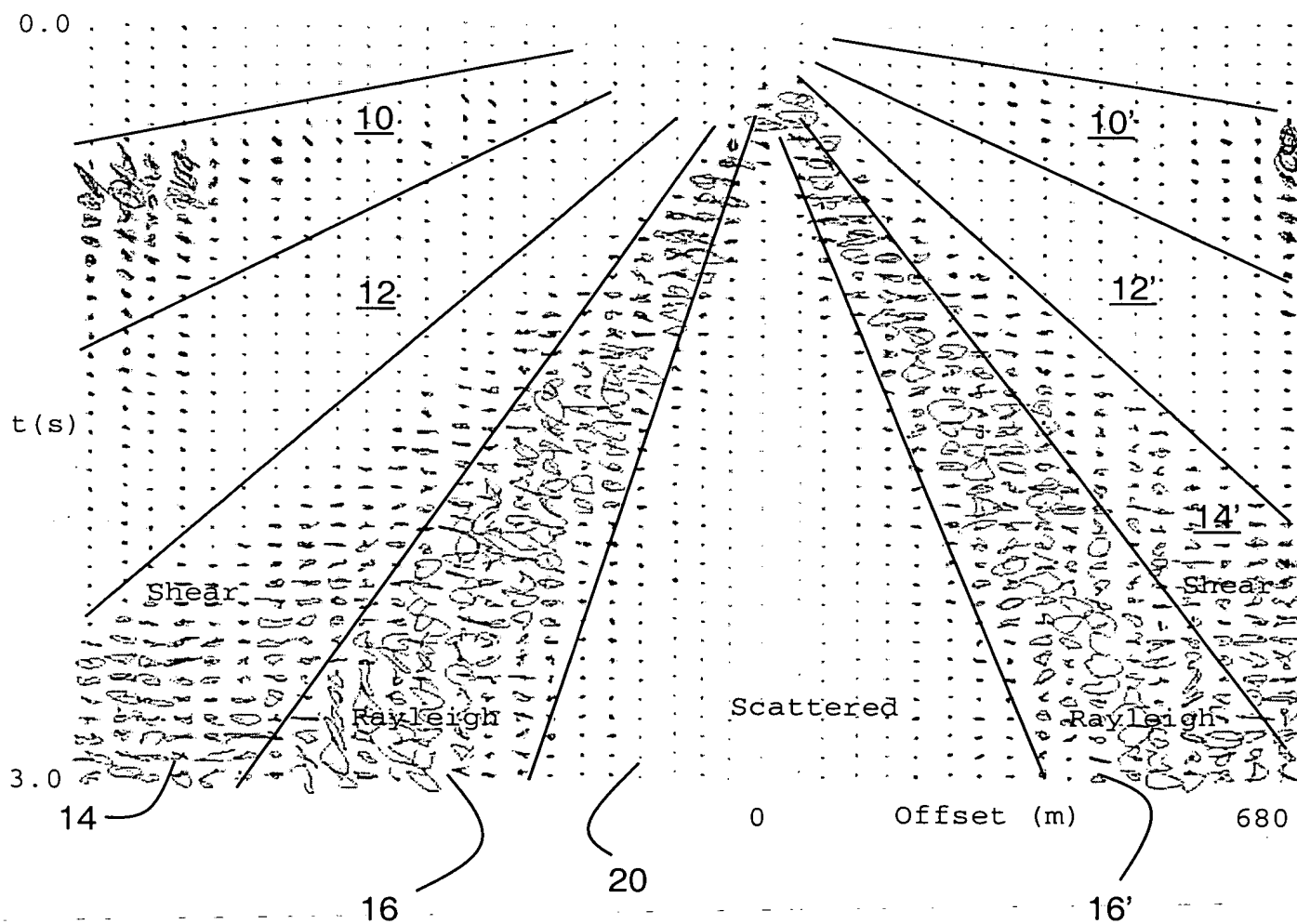


FIG. 1

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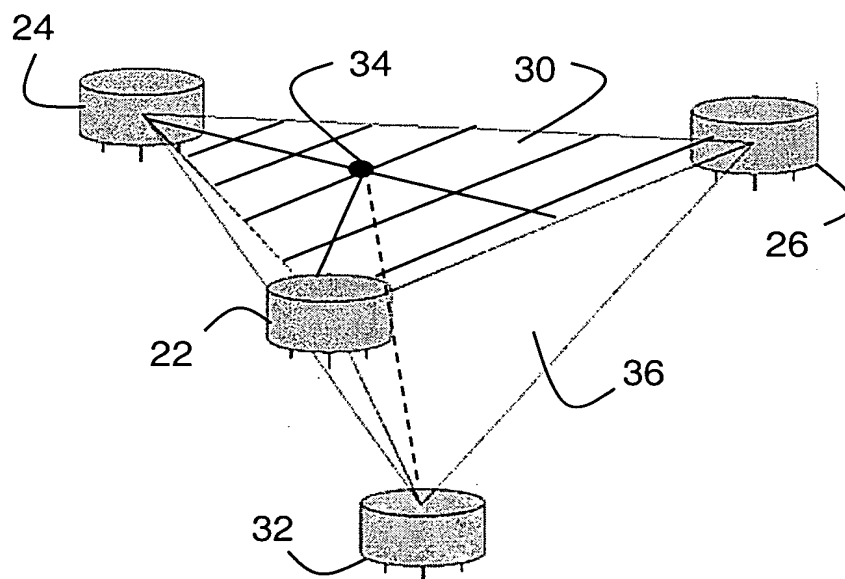


FIG. 2

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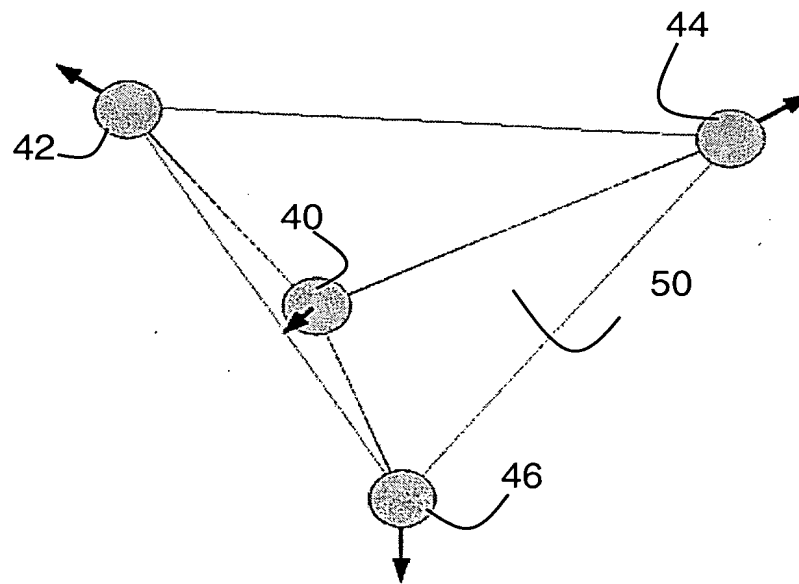


FIG. 3

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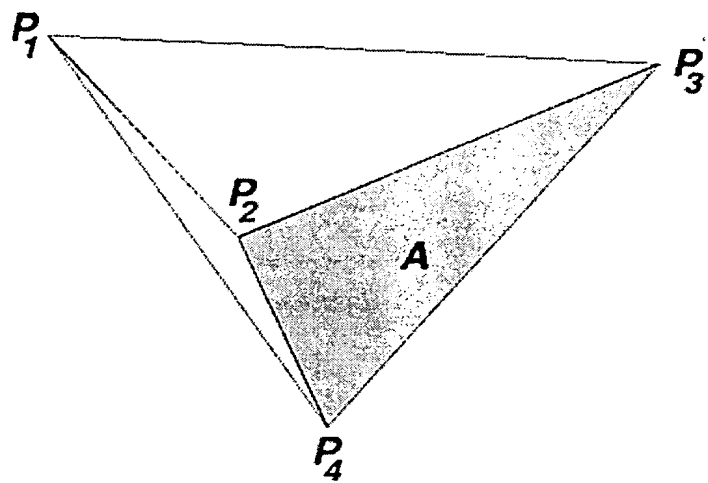


FIG. 4

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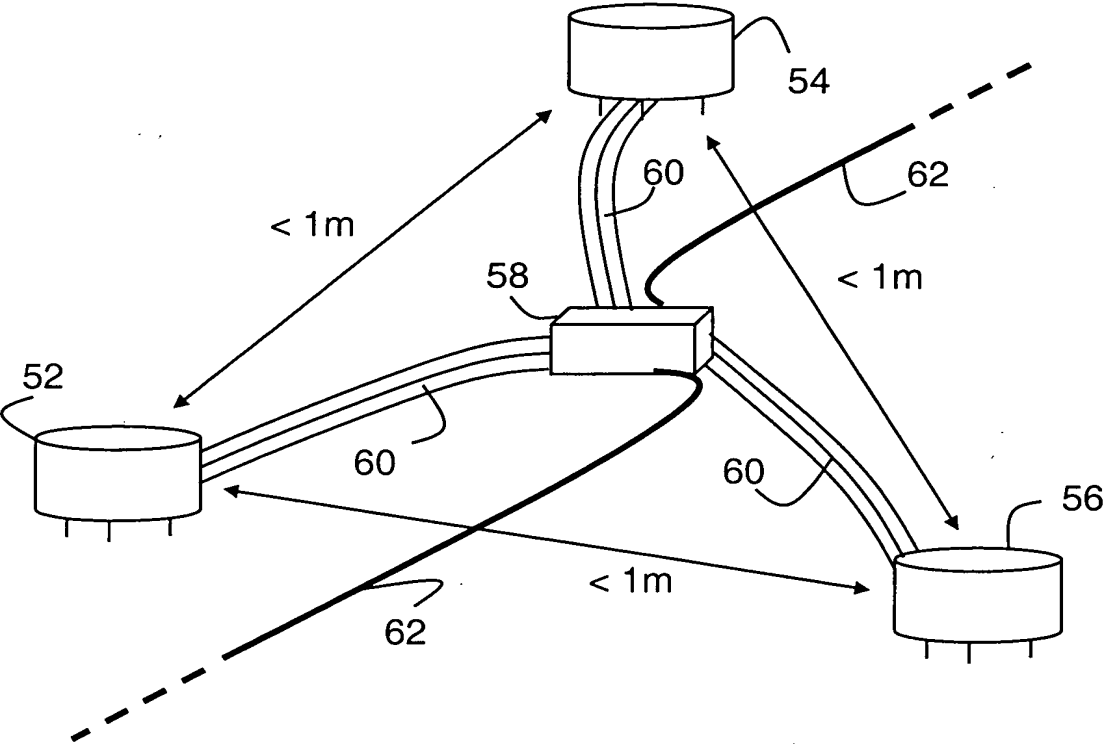


FIG. 5

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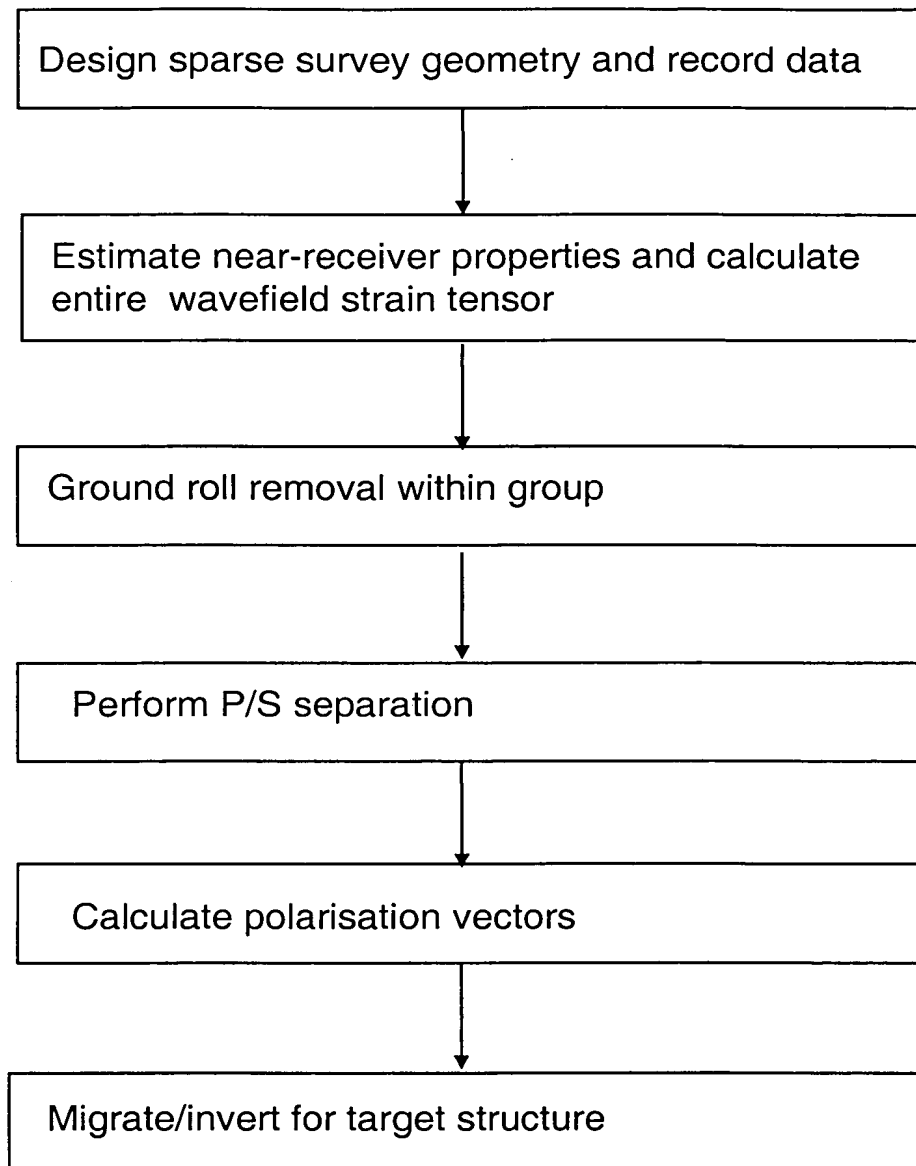


FIG. 6

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